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Polarized phase functions in oil-in-water emulsion

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Results of modeling of polarized phase functions (PPFs) in water polluted by oil-in-water emulsion are presented. The shapes of PPFs for various oil droplets size distributions and for two optically different oil types are shown for various wavelengths in the visible region. It is revealed that PPFs for two perpendicular planes are different for angles greater than 50° (with even 2-fold difference close to 90°). Shapes of PPFs depend on the type of oil and on wavelength; oil droplets size distribution plays a minor role only.

Keywords: water, scattering, phase function, spectra, oil, emulsion.

1. Introduction

Radiative transfer in aquatic environment can be derived when fundamental optical properties of water in a defined basin are known. Those properties are represented by the so-called inherent optical properties (IOPs), which are both:

– the spectrum of light absorption coefficient a (which is additive for seawater constituents),

– the volume scattering functions $\beta(\theta)$ for various wavelengths that usually are determined for clean water and separately for particles in the bulk of water suspended (θ is the scattering angle).

Sometimes, instead of volume scattering functions $\beta(\theta)$, the phase function $p(\theta)$ in connection with the scattering coefficient b are in use (the scattering coefficient b is the extinction coefficient c reduced by the above mentioned absorption coefficient a). Then $p(\theta) = \beta(\theta)/b$. Such approach to modeling of bidirectional reflectance distribution function (BRDF) of the sea area polluted by oil-in-water emulsion can be applied [1]. That modeling consists in tracing of a very big number of virtual photons (using a Monte Carlo code), and is possible thanks to the knowledge of phase function of emulsion of oil dispersed in the water. In this paper, results of the analysis of phase functions decomposed for polarization in perpendicular planes (the so-called polarized phase functions, PPFs) are reported.

2. Model of oil-in-water emulsion

The investigated model of oil-in-water emulsion consists of transparent water, in which spherical oil droplets of various diameters are suspended. Size distribution of oil droplets is known after microscopic measurements. Details of the procedure of emulsion preparation, as well as oil droplets size distributions determination, are presented in the earliest paper [2]. The same paper contains optical properties of oils used for emulsion preparation.

3. Deriving of polarized phase function

Computation of PPF of transparent media in which spherical particles are suspended on the base on Mie theory is possible [3, 4]. Also in derivations reporting in this paper the Mie theory is used. Yet, instead of integration of the oil droplets size distributions with the average of squared modules of complex amplitude $S_1(\theta)$ and $S_2(\theta)$ $(0.5\,[|S_1(\theta)|^2+|S_2(\theta)|^2])$, to calculate the parallel and perpendicular plane PPFs, integration of mentioned size distribution with the squared modules $|S_1(\theta)|^2$ and $|S_2(\theta)|^2$ respectively were used.

4. Results

The database of results obtained consists of several dozens of files containing dependences of PPFs *vs*. angle θ. Because the plots of PPFs for various droplet size distributions overlap and mutually intertwine, they are marked on the diagrams only as bands between the lowest and the highest function curve that shows Fig. 1. This plot presents PPFs for four wavelengths (350 nm, 400 nm, 550 nm, 700 nm) for both polarization planes, for two optically different oils, for angles θ exceeding 50 deg. Two maxima of PPFs are well shaped: the first at 90–100 deg, and the second one at 150–160 deg.

Maxima are shaped more visibly for longer wavelengths than for shorter ones. At the blue end of visible spectrum, the maximum at 150–160 deg for low transparent (opaque) oil *b* (Romashkino-type) disappears. Maxima for relatively transparent oil *a* (Petrobaltic-type) are always higher than for opaque oils. Values of PPFs for perpendicular polarization are even twofold higher than for PPFs for parallel polarization at 90–100 deg. Plots for other types of oil are located between indicated plots for two optically diametrically different oils *a* and *b*.

5. Discussion

To evaluate whether the calculated PPFs for oils can be distinguished from PPFs for other seawater constituents, additional runs for air bubbles were carried out. Air bubble populations were applied due to the knowledge of real air bubble size distributions for sea environment. The size distribution of air bubbles used is the averaged function

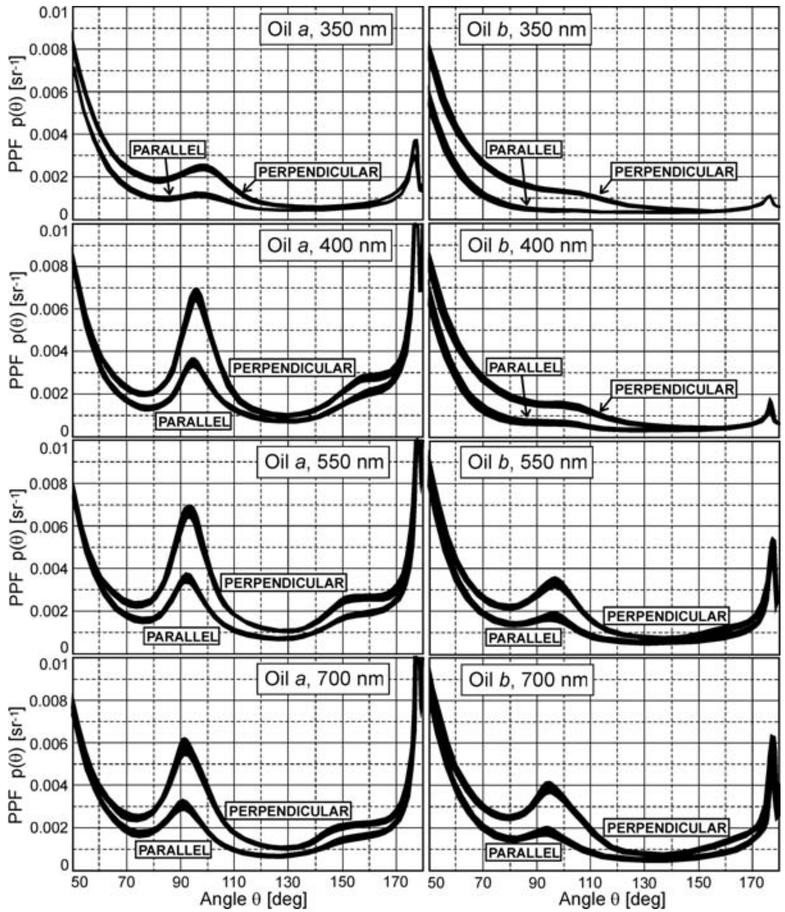

Fig. 1. Polarized phase functions for two types of oil: oil *a* – Petrobaltic-type (left column) and oil *b* – Romashkino-type (right column). Thicknesses of lines depict dissipation of plots for various oil droplets size distribution.

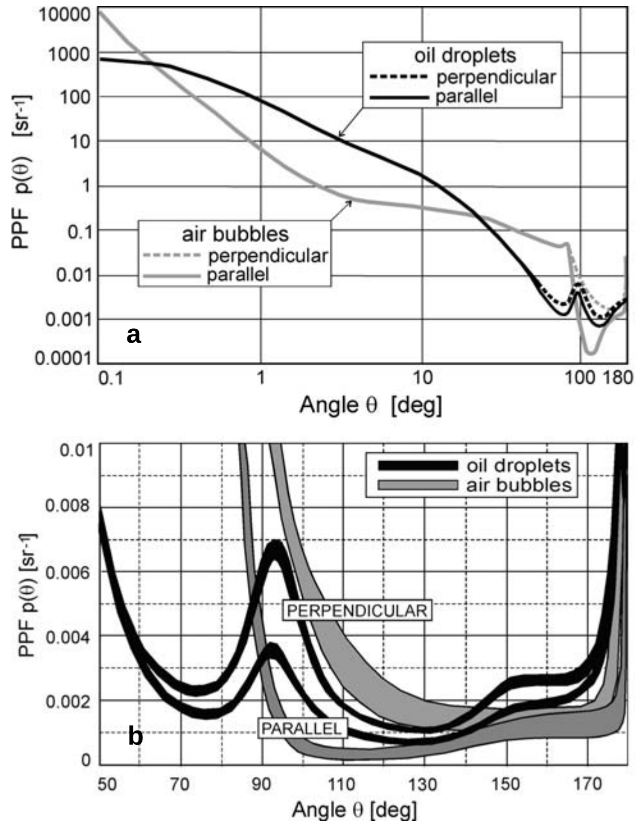

Fig. 2. Polarized phase functions for oil-in-water emulsion compared to polarized phase functions for air droplets in the seawater, both for the center of visible light spectrum (wavelength 550 nm). The lower chart shows a part of the upper one, but in narrowed range of angles. Thicknesses of lines depict dissipation of plots for various oil droplets size distribution.

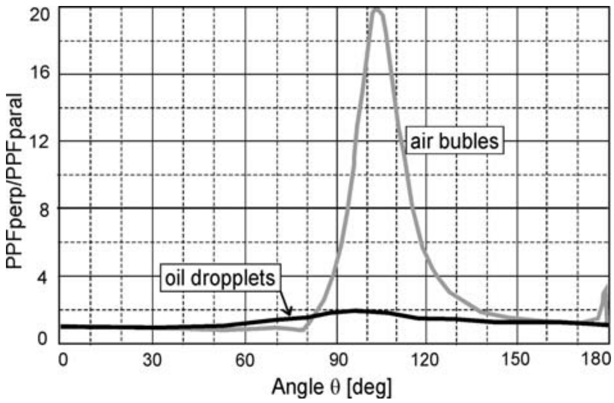

Fig. 3. The ratio PPF_{perp}/PPF_{paral} *vs*. wavelength for two kinds of suspensions in the seawater: oil droplets and air bubbles for the center of visible light spectrum (wavelength 550 nm).

derived from acoustical measurements under breaking waves for several void fraction ranges. The PPFs were calculated on the base of the size distributions, which are presented by PISKOZUB *et al.* [5]. Figure 2 is a comparison of PPFs for both oil-in-water emulsion and air bubbles. There is an evident difference between shapes of PPFs calculated for oil droplets and air bubbles. The parallel and perpendicular PPFs for air bubbles start to differ for angles exceeding 90 deg, whereas those for oil droplets start to change only for angles exceeding 50 deg. Figure 2**b** presents the same data as Fig. 2**a**, but for angles from 50 deg to 180 deg and with various size distributions of air bubbles and oil droplets in the sea environment, so they become wide bands instead of thin lines.

As Figure 2**b** shows, values of PPFs for perpendicular plane for angles in the range 70–170 deg are several times higher than for parallel plane. This difference is greatest in the range 80–120 deg. As mentioned before, index PPF_{perp}/PPF_{paral} for oil droplets reaches the value of 2, whereas for air bubbles – even 20 (Fig. 3).

Results presented in this paper should have fundamental relevance in radiative transfer modeling. One of the implementations could be the determination of BRDF of the natural surface water if a linear polarization rate of light reflected by the water surface is taken into account. Such procedure will be possible for the polarized light when photons carry virtual folders not only with current direction but also with information about polarization.

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